3. The E835 Spectrometer

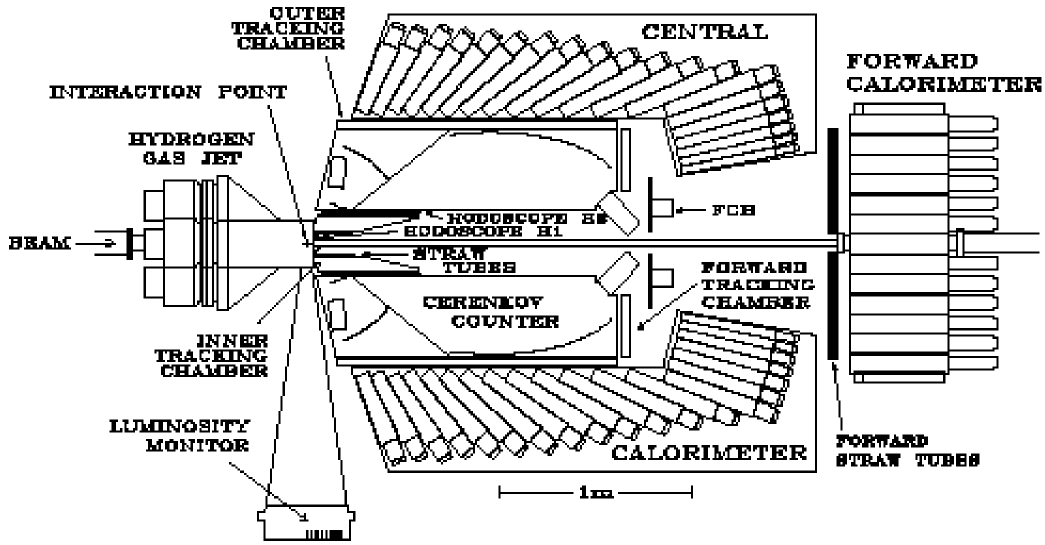

Figure 3.1 : The Spectrometer for Fermilab Experiment 760.[34]

3.1. Luminosity monitor

The luminosity monitor,[35] located in the bottom left corner of Figure 3.1, is a set of solid state detectors that is located directly below the beam pipe. Its purpose is to measure the $p\bar{p}$ differential cross section near 90 degrees. The $p\bar{p}$ differential cross section is a sum of nuclear, elastic Coulomb scattering, and interference contributions:

$$\frac{d\sigma_C}{dt} = \frac{4\pi\alpha^2}{t^2}(\hbar c)^2 G^4(t) \; ; \qquad (3.1)$$

$$\frac{d\sigma_N}{dt} = \frac{\sigma_T{}^2(1 + \rho^2)e^{-b|t|}}{16\pi(\hbar c)^2} \; ; \qquad (3.2)$$

(3.3)

and
$$\frac{d\sigma_i}{dt} = \frac{\alpha\sigma_T}{|t|} \; G^2(t) \; e^{-b|t|} \; (\rho\cos(\delta) + \sin(\delta)).$$

Knowing the acceptance of the fixed and movable solid-state detectors one can normalize the number of recoiled protons with a certain kinetic energy of the $p\bar{p}$ differential cross section. Furthermore, if one measures the amount of time that this measurement is taken, the integrated luminosity can be found. For a calculation of a cross-section, one must use the integrated luminosity, not the instantaneous luminosity. Typically in E835 the instantaneous luminosity was 2.5 X 10^{31} $cm^{-2}s^{-1}$.

3.2. Inner Detectors

Fermilab Experiment 835 uses several layers of detectors which cover the entire azimuthal range and part of the polar angle range. These are responsible for determining the polar and azimuthal angles, tracking, and helping to identify electrons.

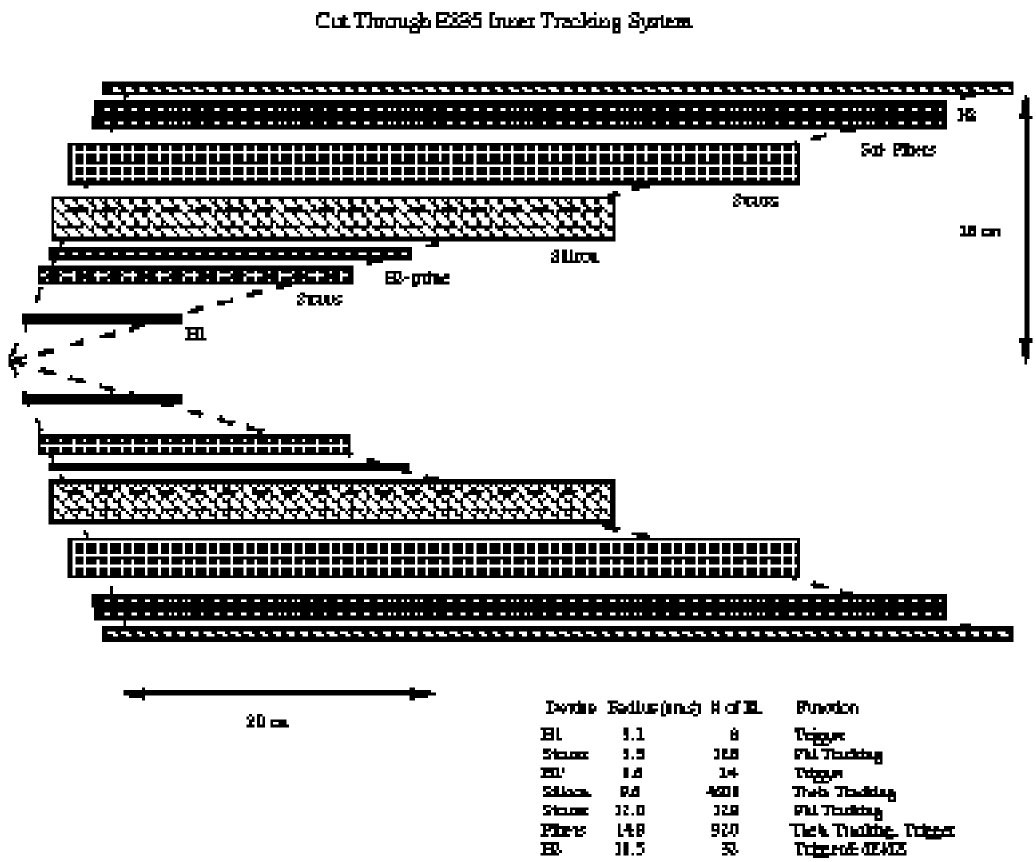

Figure 3.2 : Side View of the E835 Inner Detectors.[36]

There are 4 sets of hodoscopes: H1, H2, H2', and the Forward Charged Veto (FCV). Pulse heights from the first three hodoscopes (see Figure 3.2) help define charged tracks in the hardware trigger logic. The FCV is used to detect charged particles in the forward direction, and with H1 helps to from a veto on charged particles for the neutral trigger logic. E835 also implements two layers of straw tubes, a silicon pad detector, and a scintillating fiber tracker.

The straws, or more properly the aluminized mylar drift tubes, offer a simple, reliable, and accurate way to determine the longitudinal position and azimuthal angle for the tracking.[37] The z-coordinate of the track is determined by charge division via the amount of charge collected at both ends. The anode wire in the drift chamber best balances the competing factors of reducing thermal noise and keeping rise times for charge collection at the ends small. Typically with a gas mixture of 87.5% argon and 12.5% carbon dioxide it takes only a few nanoseconds to collect the charge created by a particle track.

The silicon pad detector[38] for E835 was designed to search for the $\varphi\varphi$ decay of the pseudoscalar states, whose primary decay channel of 2 photons is contaminated by feed-down from $2\pi^0$ and $\pi^0\gamma$ events, and the eventual decay of each φ into charged kaons. Its spatial resolution of 2 mrad in azimuth and 3 mrad in the lab polar angle and fast readout also serve to correlate spatial measurements from the other inner detectors. This cylindrical detector covers 360 degrees in azimuth and 15 to 65 degrees in the lab polar angle.

Another measurement of the lab polar angle was given by the scintillating fiber tracker.[39] The two-layer tracker (radii of 14.4 cm and 15.06 cm) can accommodate the increased luminosity of E835 over E760 by delivering an efficiency of more than 99% during peak luminosity runs. Light coming from each of the 860 fibers (core radius of 370 μm) is read out by solid state devices called VLPC's (Visible Light Photon Counters) with a high quantum efficiency (i.e. a very high signal-to-noise ratio). Like the silicon pad detector, the fiber tracker covers 15 to 65 degrees in lab polar angle and 360 degrees in azimuth.

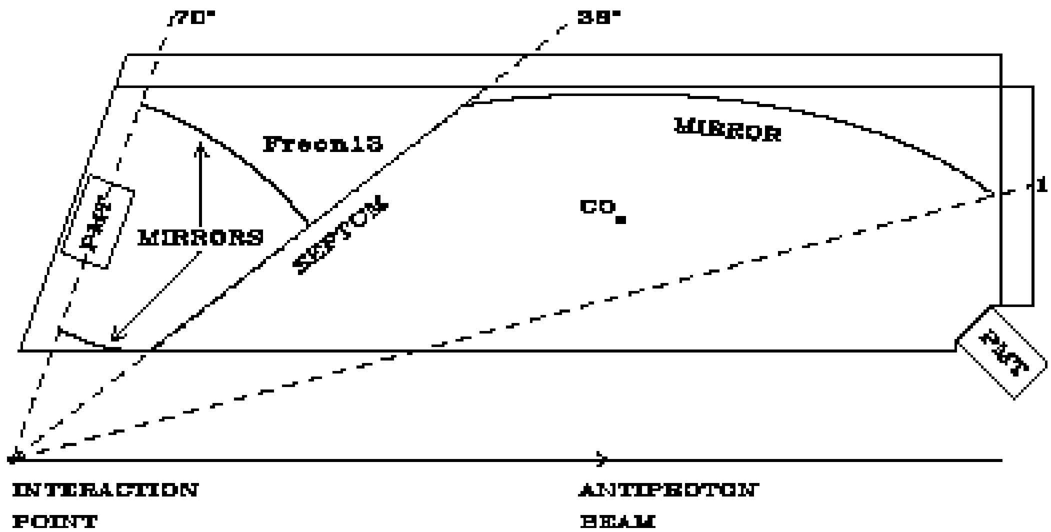

Figure 3.3 : Cross section of the Cerenkov detector.[40]

A threshold gas Cerenkov detector[41] (Figure 3.3) serves to reject charged pions from electrons, and thus help one pick out an electromagnetic signal from the huge hadronic background. It is divided into 8 azimuthal sections (45 degrees each), with each of these divided into 2 polar regions with 2 different gases. Each of the polar regions are operated at atmospheric pressure and room temperature.

On one hand, the gas chosen had to have an index of refraction small enough so that the threshold velocity at which Cerenkov light was produced ($\beta_{th} = 1/n$) was higher than the velocity of either pion from the direct production of 2 charged pions. On the other hand, it had to be large enough to maximize the yield of Cerenkov light. Furthermore, both gases had to be low light-absorbing and non-explosive. As a result, CO_2 was chosen for the forward region and Freon 13 for the backward region. Cerenkov light was then reflected by mirrors onto photomultiplier tubes, and then read out by analog to digital converters (FERA).

3.3. Central Calorimeter

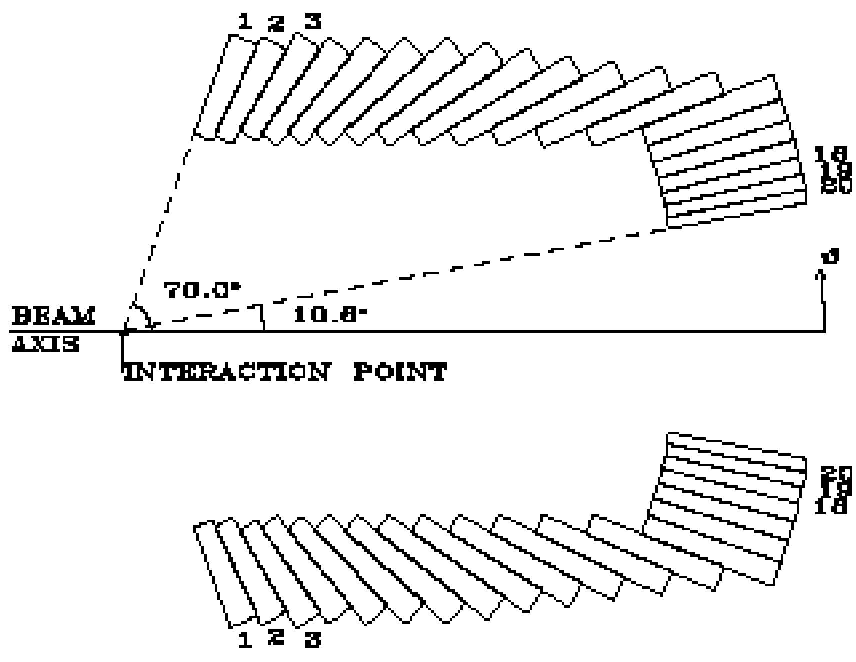

Figure 3.4 : One wedge of the Central Calorimeter.[42]

The heart of the experiment is the central calorimeter (CCAL). The CCAL consists of 1280 lead-glass blocks arranged so that there are 20 'rings' (Figure 3.5) and 64 'wedges' (Figure 3.4). Each of the 64 blocks in a particular ring shares the same polar angle (20 rings X 64 wedges/ring = 1280 blocks), and each of the 20 blocks in a wedge shares the same azimuthal angle (64 wedges X 20 blocks/wedge= 1280 blocks). The CCAL covers the entire azimuthal range and all polar angles between 11 and 70 degrees, where the z-axis is defined by the direction of the antiproton beam. The faces of all 1280 blocks point towards the center of the interaction region where the antiproton beam intersects with the hydrogen gas jet.

Each lead glass block responds to photons and electrons by creating electromagnetic showers. When these shower particles travel faster than the speed of light within the lead glass, they produce Cerenkov light, which is collected by Hamamatsu photomultiplier tubes.

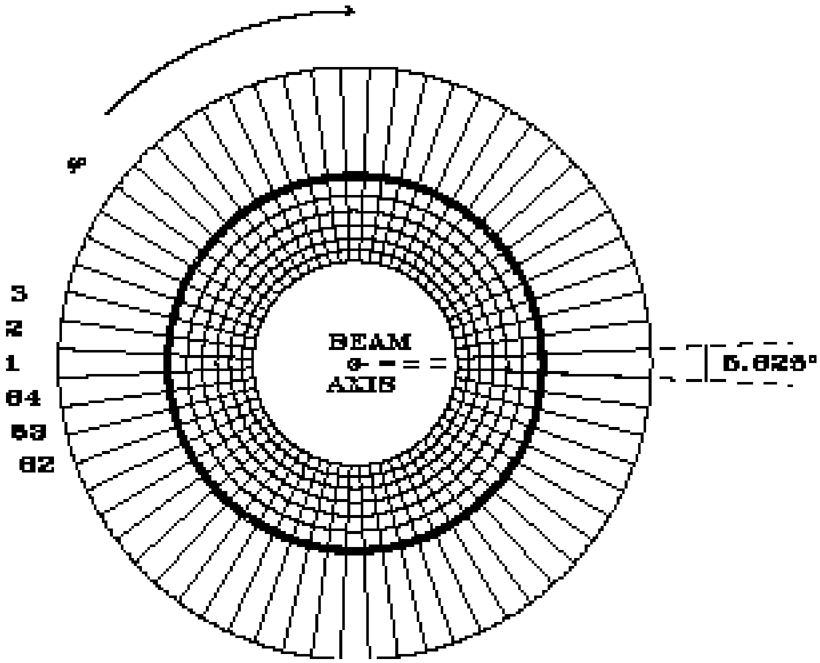

Figure 3.5 : One ring of the Central Calorimeter.[43]

The CCAL was designed to identify the charmonium signal from a large background, which primarily comes from the process $p\bar{p} \rightarrow 2\pi^0$. If one or both of the π^0's decay asymmetrically and the low energy photon is not detected, then this event may mimic a 2γ or a 3γ event. As a result, photons with an energy of greater than 50 MeV must be detected with an efficiency of greater than 95 %. On the other hand, it has to resolve both photons from a symmetric π^0 decay, where the opening angle can be quite small.

The granularity of this calorimeter was found via a Monte Carlo simulation, which required that a symmetrical π^0 would produce two resolvable clusters in the CCAL at the highest formation energy intended for the experiment. Each of the lead-glass blocks subtends different polar angles as a result: 1.1 degrees in the forward direction to 5.2 degrees in the backward direction. Using the same Monte Carlo, it was shown that in order to reject background events, it is more critical to contain as much of the shower as possible for low energy photon detection than it is to optimize the energy resolution. Thus block lengths were chosen to contain 90-95 % of the shower's energy.[44]

The CCAL is calibrated by looking at $\pi^0\pi^0$ events.[45] During data taking, an event is selected to be written to a calibration tape. A DST (Data Summary Tape) is produced to include $\pi^0\pi^0$, $\pi^0\eta$, and $\eta\eta$ events that have an acoplanarity < 0.1 and akinematics < 0.05. Acoplanarity measures how different the two mesons come out in their azimuthal angles, and akinematics measures how different the two mesons are produced in their center-of-mass polar angles. If the event is an exclusive 2-meson event, the mesons are produced back-to-back in the center-of-mass, and both these quantities are zero.

The CCAL cluster thresholds are set at 25 and 50 MeV (at least 25 MeV for the seed block, and at least 50 MeV minimum for an entire cluster). The offline clusterizer routines reconstruct events from the energy deposits in the central calorimeter by searching for "seed" blocks around which to build a cluster of energy deposits representing a particle track through the CCAL. No timing cuts are incorporated for the clusters via the TDC's (time to digital converters), but only events with 4 clusters get written to the DST, which is used to determine the location of the interaction vertex in the subsequent analysis.

Once the DST has been created, a subset of $\pi^0\pi^0$ events are selected. Here the acoplanarity must be less than 0.032, the akinematics must be less than 0.01, and the mass of each reconstructed π^0 must be within 40 MeV of the π^0 mass quoted by the Particle Data Group, 135 MeV. Gain constants are evaluated by iterating over this subset using the pedestal subtracted adc count (analog to digital conversion produced by the FERA's) for each block. These new gain constants are used to find $\pi^0\eta$ events in this DST, and one scales these gain constants in order to arrive at the proper mass of the η, 548 MeV.

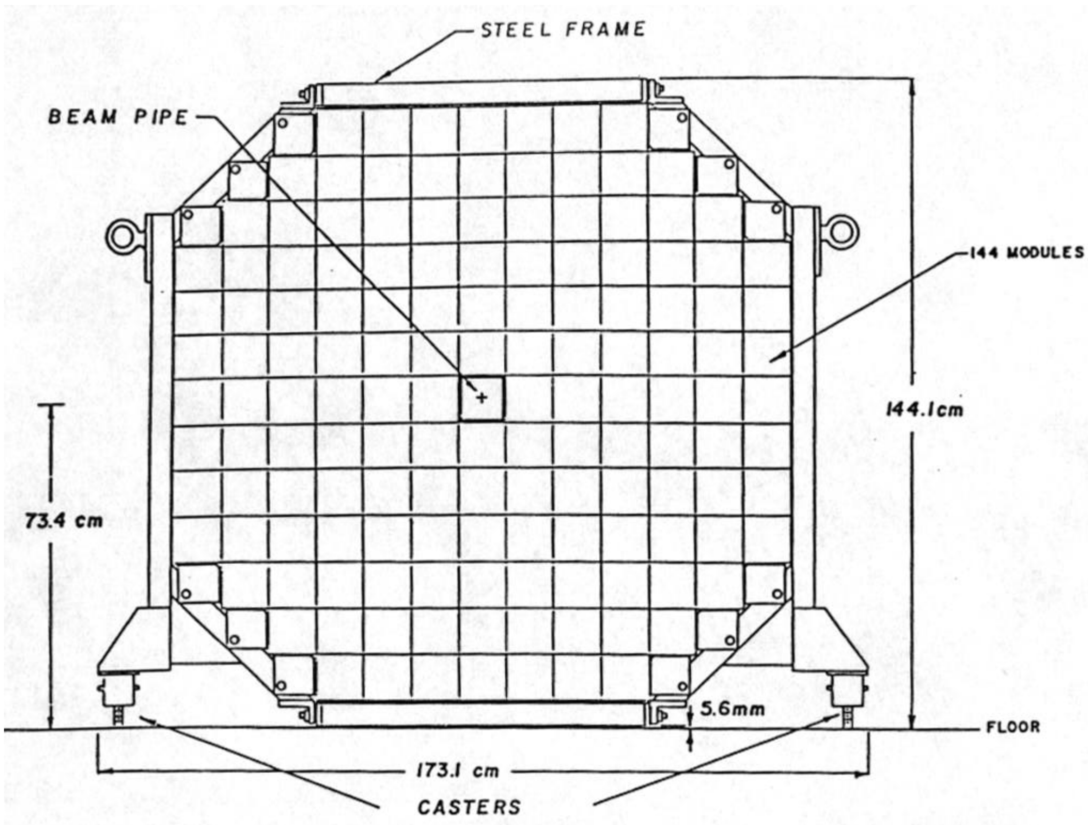

Figure 3.6 : Front view of the Forward Calorimeter.[46]

3.4. Forward Calorimeter

A forward endcap calorimeter (Figure 3.6) is also included among the detector elements of the experiment. Since the charmonium signal must be extracted from a huge hadronic background, the forward calorimeter must be able to detect single photons down to about 60 MeV. The largest background to the decay $\eta_c \rightarrow \gamma\gamma$ is $2\,\pi^0$, and either both π^0's decay asymmetrically or one of the soft photons are not detected and thus this channel can contribute to the background for the η_c.

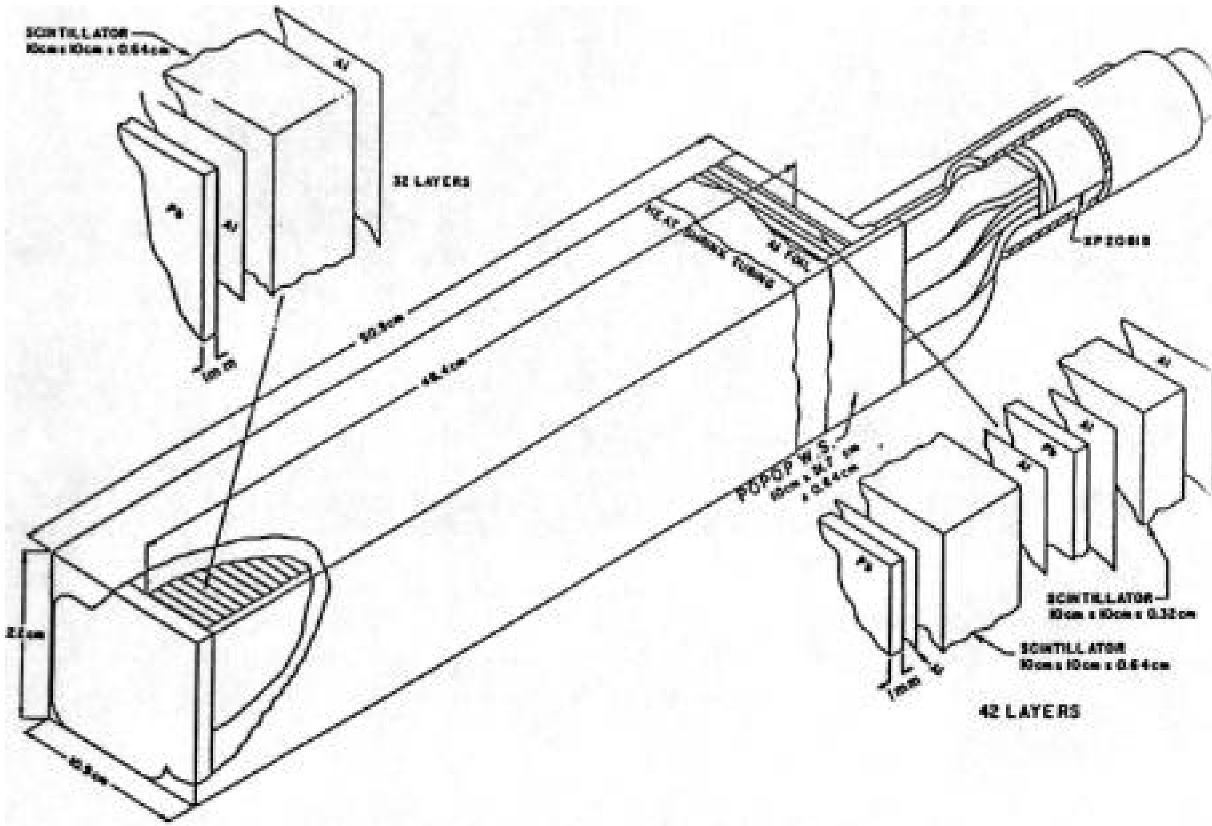

Figure 3.7 : Forward Calorimeter Module.[46]

The forward calorimeter[46] is a sampling electromagnetic calorimeter. Centered upon a 13X13 grid that is 3 meters from the interaction point, with the beam pipe going through the center, 144 modules are stacked at the end of the central calorimeter. Blocks do not exist at the corners of 13X13 grid since this area is blocked by the central calorimeter. Each module is 51 cm long and has transverse dimensions of 10 cm X 10 cm. Within each module are 148 alternating layers of lead and acrylic scintillator that were compressed and shrink-wrapped together. A POPOP wavelength shifter lies along one side of each FCAL module to transmit light to the PMT's (photomultiplier tubes) and on to the data acquisition system.